

# Interaction between interconnected and isolated grounding systems: A case study of transferred potentials

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**Abstract**— The effect caused by ground fault current in a complex system of interacting electrodes is theoretically studied. The calculation applies to a specific case in which a set of interconnected electrodes, which are part of a grounding facility network, are activated by a ground fault current. Transferred potentials to adjacent passive electrodes are calculated and the most relevant parameters of the electrode system are evaluated. Finally, the convenience of connecting the grounding electrodes is discussed.

**Index Terms**— Transferred potentials, grounding analysis, thin wire structures, earth fault, Method of Moments.

## I. INTRODUCTION

The grounding systems (GS) are an essential part of the distribution networks of electrical power. Proper design of these systems prevents the occurrence of anomalous potential that can be dangerous to people and damage sensitive equipment and other neighboring facilities. The situations in which such a GS is indicated ranges from fault currents in electrical systems due to a malfunction, to an eventual lightning stroke. In any situation, the main target of a GS is to ensure that their electrical resistance is low enough to guarantee that fault currents dissipate mainly through the grounding grid into the earth, while maximum potential differences between close points on the earth's surface must be kept under certain tolerances (step, touch, and mesh voltages) [1], [2].

In real GSs, we should take into account not only the conductors directly involved in the installation to be protected, but also any other conductor, connected to it or not, that can interact with the whole GS in case of activation [3]. The transfer of potentials between the grounding area and outer points by buried conductors, such as communication or signal circuits, neutral wires, pipes, rails, or metallic fences, may produce serious safety problems [4],[5]. It is also important to take into account the metal structures of the neighboring

buildings of the protected area because there may appear transferred contact potentials out of the tolerance range [6],[7]. The ground potential rise (GPR) due to electrical current dissipation to the ground is a well known and studied phenomenon from the equations of electromagnetism [8]. However, in practical situations, many difficulties may appear which greatly complicate obtaining a solution. The shape of the electrodes and their spatial arrangement together with the possible interconnection of some of them, establish multiple boundary conditions added to the problem which can greatly complicate reaching an acceptable solution, which is obtained in most cases by applying numerical methods [9]-[12].

In this paper, we consider a section of the electric power network of an urban area, where several Secondary Substations (SS) can be found together with their corresponding GS. In the case of study, the GSs of all the SS considered, are interconnected via the underground cable shield that transmits power to the SS. Besides ensuring an equal electric potential of all the interconnected GS electrodes, the effect produced by such networking is the distribution of the fault current between all the GS electrodes and consequently, as discussed in this paper, smoothing the potential profile in the ground. As can be seen from the results, an appreciable drop in the contact potential profile will be found. Another goal of this work is to calculate the potential appearing in various isolated metal structures scattered nearby. For this purpose, a low frequency electrical fault current is released from one of the SS to its GS and from there, it is driven into the electrically homogeneous soil through the whole system of interconnected GSs. As mentioned before, a fault current in any of the GSs produces an electric current to ground at all the interconnected GSs, so that the potential is maintained at a fixed value on all of them. The current released into the ground results in GPR affecting any surrounding metallic body. The result is the creation of a system of interacting conductors in which mutual interaction needs to satisfy the conditions imposed on the system. This is on one hand the constancy of the potential of all of them and secondly, the integral equation that specifies how to calculate the potential at any point of the domain, needs to contain the net current released by the system of active electrodes. To complete the scheme, there should be added the possible boundaries separating material media possessing different electrical properties and therefore it is necessary to specify the behavior of the quantities of interest on either side of these boundaries.

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The present paper is organized as follows: After the introduction considered as section 1, the theoretical foundation and calculation scheme that has been used is presented in section 2. This section considers the interconnection between the active electrodes and leading to boundary conditions imposed on the overall system of equations to be satisfied by the entire electrode. In section 3, the scheme presented is applied to a real configuration corresponding to a section of the GS network of Benidorm, city on the Spanish Mediterranean coast, in the Autonomous Community of Valencia. In this section the results are discussed and step and touch potentials are evaluated. Furthermore, the consequences of interconnecting the GS electrodes are discussed. Finally, the conclusions of this work are summarized in section 4.

## II. THEORETICAL FOUNDATIONS

The problem of finding the potential profile, step, touch, and mesh voltages, created by a system of conductors in mutual interaction, can essentially be solved by finding a solution of the Laplace equation that satisfies a set of boundary conditions which define univocally the configuration of conductors and their electrical state.

Assuming we have  $P$  conductors  $C_i$ , with  $i=1..P$ , in a semi-infinite soil of conductivity  $\sigma$ , of which  $Q$  are interconnected and dissipate together an electric current  $I$ , the equations that needs to be solved are

$$\begin{aligned} \vec{\nabla} \phi &= 0 \\ \phi(\vec{r})|_i &= V_i \\ \vec{n} \cdot \vec{\nabla} \phi|_G &= 0 \end{aligned} \quad (1)$$

where  $\phi(\vec{r})|_i$  is the value of the potential on the conductor  $C_i$  and the last equation accounts for the semi-infinite medium starting from the boundary  $G$ . Since  $Q$  conductors are interconnected, their potentials needs to be equal. Furthermore, if  $I_i$  is the electric current released by the conductor  $C_i$ , the interconnection of the  $Q$  conductors entails that the potential of those conductors are equal and the intensity dissipated altogether  $I_G$ , is  $I_G = \sum_{j=l+1}^{l+Q} I_j$ .

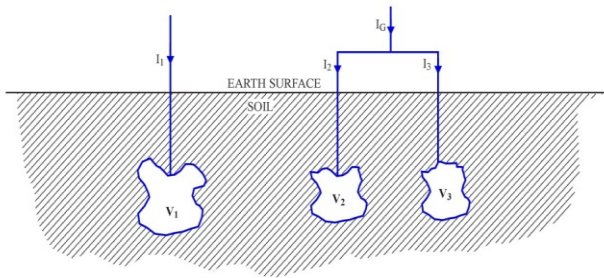


Fig 1. A general configuration of interacting electrodes. Here  $V_2$  equals  $V_3$  due to electrical connection.

By using the second Green identity, the result is a formal solution of (1) for each point of the domain, excluding the borders, which, in this particular case, are the surfaces of the conductors and also the ground surface, supposing this last horizontal and perfectly flat

$$\phi(\vec{r}) = \sum_{i=1}^P \iint_{S_i} -\rho \frac{\partial \phi(\vec{r}_i')}{\partial n} G(\vec{r}, \vec{r}_i') dS(\vec{r}_i') \quad (2)$$

where  $\rho$  is the soil electrical resistivity, and the symbol  $\partial/\partial$  stands for the gradient projection along the unitary vector  $\vec{n}$  normal to the surface  $S$ , i.e.,  $\partial/\partial n = \vec{n} \cdot \vec{\nabla}$ . The integrand  $-\frac{\partial \phi(\vec{r}_i')}{\partial n}$  can be associated with a surface density of current released to the soil (leakage current) through the conductor surface. On the other hand, the symbol

$$G(\vec{r}, \vec{r}') = \frac{1}{4\pi \vec{r} - \vec{r}'},$$

stands for the Laplacian Green function. Equation (2) is an integral equation for the potential  $\phi(\vec{r})$  whose solution is not easier to solve (1) unless it is possible to make some substantial simplifications. This is the case when the electrodes are thin wires. Under these conditions, the (2) is reduced to a sum of contributions of filaments which release current to ground and are located on the axis of the electrodes.

$$\phi(\vec{r}) = \sum_{i=1}^P \int_{L_i} \rho \lambda(\vec{r}_i') G(\vec{r}, \vec{r}_i') dl(\vec{r}_i') \quad (3)$$

where  $\lambda(\vec{r}_i')$  stands for the electric current density released to the soil along the filament axis  $l_i$  which replaces the whole conductor  $C_i$ . Equation (3) is valid for both points within the domain as well as for points at the border, in particular on the surface of conductors, as long as the current distribution released to the ground  $\lambda(\vec{r}_i')$  is known. Equation (3) is commonly referred as Electric Field Integral Equation (EFIE) associated to (1).

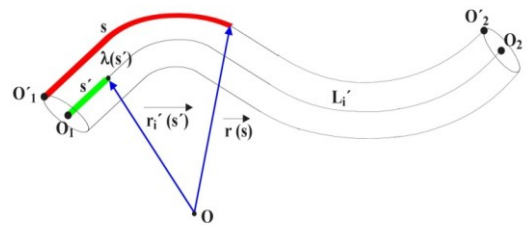


Fig. 2. A conductive curved thin wire where some of the variables used in the text are shown.

Taking advantage of the thin wire model, the coordinates  $s$  and  $s'$  as shown in Fig. 1 will be used. Thus, the position vectors of points defining the axis and surface of the conductors are functions of the coordinates  $s$  and  $s'$  respectively. For each point on the thin wire conductor surface  $L_i$  the potential is

$$\phi(s_i) = \sum_{j=1}^P \int_{L_j} \rho(s_j) G(s_i, s_j) ds_j \quad (4)$$

which has a constant value of  $V_i$  for any point  $s_i$  on the surface of the conductor  $C_i$ .

The analytical resolution of (1), (2), (3) or (4) is only possible in very few cases, depending strongly on the geometry of the conductors. In practical situations, such as in the present work, it is almost always necessary to use a numerical scheme for the calculation of the solution. A widely used numerical method is the Method of Moments (MoM) described briefly below.

The MoM is a numerical procedure that allows obtaining a solution to equation (4) by reducing the integral equation to a matrix equation [9],[10]. To do this, the overall curved wire of length  $L$ , is divided into  $N$  small sized line segments  $\Delta = L/N$ . A selected set of known functions is chosen to build a linear approximation to the unknown function  $\lambda(s')$ ,

$$\lambda(s') = \sum_{n=1}^N \lambda_n \cdot u_n(s') \quad (5)$$

as an example, the unit step function can be chosen for  $u_n(s')$ ,

$$u_n(s') = \begin{cases} 1 & \text{if } (n-1)\Delta < s' < n\Delta \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

Note that this is a staircase-like approximation to the function  $\lambda(s')$  that represents the leakage current distribution along the wire axis.

The choice of these functions  $u_n$  is made for simplicity, but they are neither the only possible nor the best numerical results to be provided. In this paper, the functions (5) were chosen because of their simplicity at the risk of losing some accuracy in the final results [13],[14].

$$\phi(s_i) = \sum_{j=1}^P \sum_{n_j=1}^N \lambda_{n_j} \int_{\Delta s(n_j)} \rho(s_i, s_j) ds_j \quad (7)$$

To complete the numerical scheme, it is necessary to discretize  $\phi(s_i)$  along the conductor surface. This can be done using Dirac Delta functions as weighting functions. In this case we use sampling points on the conductor surface which are denoted by  $s_i = n_i \Delta$  leading to the so called matching point scheme

$$\begin{aligned} \phi(s_i) &= \int_{L_i} \phi(s_i) \delta(s_i - m_i \Delta) ds_i = \\ &= \sum_{j=1}^P \sum_{n_j=1}^N \lambda_{n_j} \int_{\Delta s(n_j)} \rho(s_i, s_j) ds_j \end{aligned} \quad (8)$$

which results in an  $N \cdot P$  equation system with  $N \cdot P$  unknowns, which are the currents  $\lambda_{n_j}$  associated with each segment of each thin wire conductor of the whole system.

If instead of Dirac Delta type weight functions, we use the same functions (6) as weighting functions, we call it the Galerkin Method obtaining

$$\begin{aligned} \phi(s_i) &= \int_{L_i} \phi(s_i) u_n(s_i) ds_i = \\ &= \sum_{j=1}^P \sum_{n_j=1}^N \lambda_{n_j} \int_{\Delta s(m_i)} \int_{\Delta s(n_j)} \rho(s_i, s_j) ds_i ds_j \end{aligned} \quad (9)$$

There should be pointed out that both in (8) and (9),  $\phi(s_i) = V_i$  at any point of the conductor  $C_i$ . Furthermore, these potentials  $V_i$  are not initial data of the problem, although the total current released by each isolated electrode  $I_i$  and the overall current  $I_G = \sum_{j=1}^{l+Q} I_j$  released by the interconnected electrodes are initially known. All this information needs to be entered into the system of equations that satisfies the electrode configuration and the solution is given in terms of the absolute potential. The equation (8) has been implemented, together with the initial data of the problem, by using a Matlab code entirely written by the authors. In general, the practical implementation of the MoM is clearly stated in references [9] and [10], where some details of our code can be found.

A final calculation is necessary to express the final result in terms of quantities of interest from the electrical point of view. This is the calculation of step and touch potentials associated with each point on the ground and each passive electrode (which does not release current to the soil). The step potential, defined as the potential difference between two points on the earth separated by a distance of 1 m, is approximately the value of the tangential electric field at the ground surface. The contact potential at a point of the earth surface is the difference between the common potential of the active electrodes and the absolute potential of that point on the earth surface (Fig. 3).

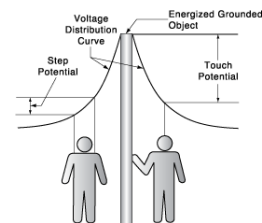


Fig 3. Step and touch potentials.

### III. APPLICATION TO A PART OF THE GS NETWORK IN THE CITY OF BENIDORM, AUTONOMOUS COMMUNITY OF VALENCIA, SPAIN.

The calculation method presented in Section 2 will be applied to a system of conductors composed by SS grounding electrodes and consumer facilities equivalent electrodes. Unlike TN earthing systems in which a global earthing system is achieved, ours is formed by a TT earthing system where there is no connection between the consumer electrodes and the corresponding to SS grounding electrodes, these last being joint by the shield of the underground cable. In this paper, the conductors forming part of the GS network comprises three active electrodes, interconnected to each other, which correspond to three SS located in the study area.

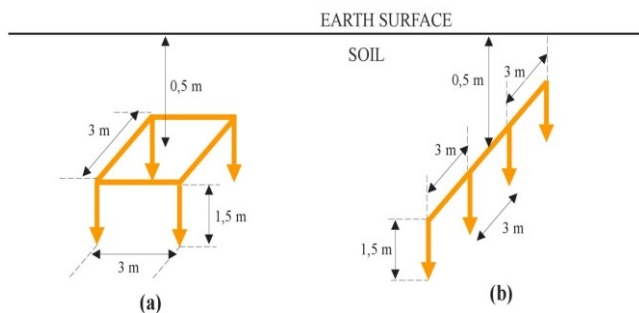


Fig. 4. Main features of the grounding electrodes used in the GS of Benidorm.



Fig. 5 A snapshot of the area under study (upper panel). The lower panel shows a diagram of the power distribution network.

Two of these electrodes have the shape of a horizontally rectangular frame, vertical rods at their corners and dimensions as shown in Fig. 4 (a). The third comb-like electrode is shown with dimensions in Fig. 4 (b). They were buried at a depth of 0.5m. The ground is considered electrically homogeneous with resistivity  $200\Omega\text{m}$ . Since a piecewise-constant representation (5) gives rise to an interpolation error of order  $\Delta = l/N$ , we have chosen a number  $N=50$  of segments per linear section of the electrodes, in order to reduce the error to less than 0.1% [14]. Slightly better results can be achieved with a piecewise-linear representation, but at a much higher computational cost.

In the area under study, there are several customer facilities as residential buildings, hotels, shopping centers and recreational facilities such as a swimming pool and parking spaces.

All these buildings, although they are not directly connected to the GS network, have metallic structures that are sensitive to the energization of the GS electrodes, and therefore, they can become part of a complex system of interacting electrodes, acquiring an electric potential transferred by the activated GS network.

The upper panel of Fig. 5 shows an aerial image of the actual work environment, while lower panel shows the positions of the SS joint by the power cable (dashed line).

It is assumed that users of grounding systems have followed the Spanish low voltage legislation on buildings, so that each building considered in this work is modeled as a rectangular thin wire electrode of the dimensions and orientation to approximate the actual building which is placed parallel to the ground surface and, as the GS active electrodes, buried at 0.5m under the ground surface. Here we have assumed that the GS electrodes have the same positions as those of the associated SS, as shows Fig. 6.

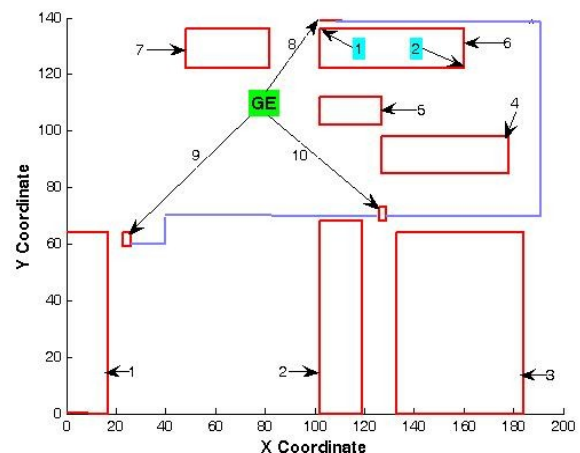


Fig. 6 Geometrical layout of the electrode system. The electrodes marked with the numbers 8, 9 and 10 correspond to the GS electrodes associated with SS.

Figure 7 shows the results when the interconnection between SS electrodes is ignored. To that aim, first it is assumed that a fault current of 130A is released only by electrode 8. Regardless of the existence of the electrodes



representing adjacent buildings and the remaining electrodes of the system, the ground potential profile is shown in the upper panel of Fig. 7. The grounding resistance  $R_G$  of the electrode is found to be 23.083 Ohm, while the electrode potential is 3000V. With this simplified method, it is usually assumed that the closest electrode, i.e. number 6, obtains the potential associated with point closest to the SS (point 1 on a blue background of Fig. 6), i.e.  $V_1=791V$ . With this approach, a critical touch voltage of 716V appears at point 2, given that touch voltage is the difference between the voltage of the electrode 6 and the ground potential adjacent to the point 2 ( $V_2=75V$ ), so  $V_t=V_1-V_2=716V$ .

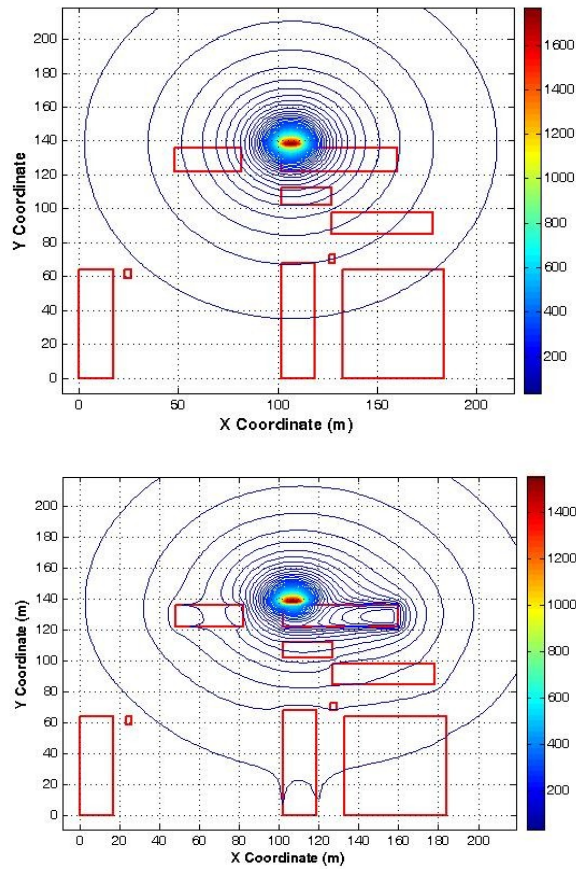


Fig. 7 GPR obtained by activating only the electrode 8 of GS regardless adjacent buildings (left side). On the right side is also shown the GPR but adding all the system electrodes.

However, this critical touch voltage changes dramatically when adjacent conductors are taken into account. The lower panel of Fig. 7 shows the ground potential profile supposing again a fault current of 130A released only by the electrode 8 but considering the interaction with the electrodes of the rest of the system. This time, the active electrode potential is slightly lower (2830V as can be seen in Table 1) which implies a reduction of the grounding resistance by 5.65% due to the buried conductors in the proximity of the SS electrode. Nevertheless, the main changes are related with the adjacent building voltages (mainly electrode 6) which acquires a potential three times lower, as a result of the interacting

system of electrodes, that is found to be  $V_1=238V$ . Moreover, the ground potential at the point 2 is very close to the electrode 6 voltage  $V_2=190V$ , so the touch voltage at point 2 is not so critical since it is  $V_t=V_1-V_2=48V$ , fifteen times lower than the one considered with the previous method..

Similarly, Fig. 8 shows the ground potential profile when the fault current is released by the electrodes numbered 9 (upper panel) and 10 (lower panel) and the rest of the electrodes are included in calculations as an interacting system of electrodes.

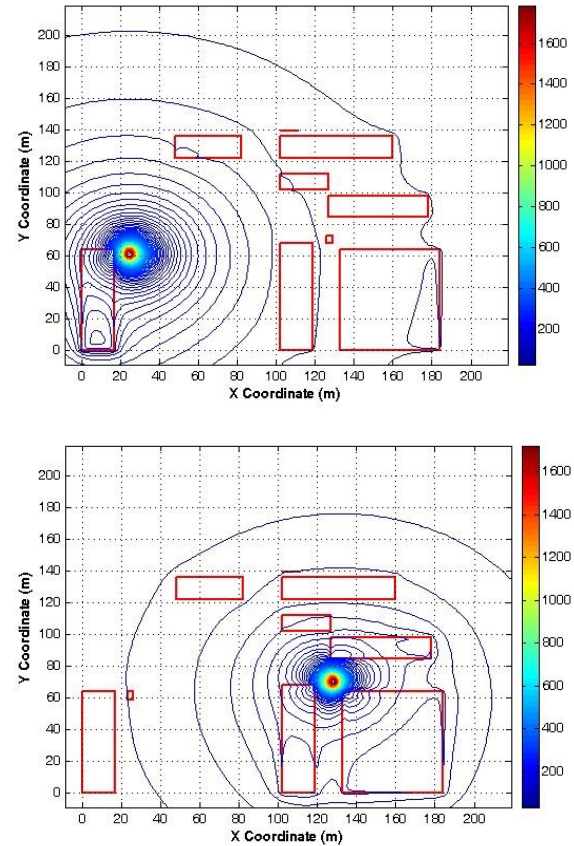


Fig. 8 GPR when electrodes 9 and 10 are activated and all the electrodes are taken into account.

Table 1 shows the most relevant data of the GS electrode system when all of them are independent, i.e., there are no interconnections between them and a fault current of 130A is released from electrodes 8, 9 and 10 respectively.

The above mentioned result would be representative of a network without ground interconnection, for instance, a network fed by overhead lines. However, the actual situation of underground networks in which the electrodes are interconnected by means of the cable screens, is completely different. In this circumstance, a fault in any of the SS, gives rise to ground currents through all the electrodes (three in the considered case) simultaneously. In this case the current fault of 130A will be shared between all the interconnected electrodes of the GS network. Under these conditions, the absolute potential profile in the ground is as shown in the Fig. 9. This figure shows all the electrodes that form part of the

TABLE 1.  
ELECTRICAL FEATURES OF THE ELECTRODE SYSTEM WHEN THE FAULT CONDITION IS ON ELECTRODE 8, 9 AND 10, AT THE SUPPOSITION OF NON CONNECTED GS ELECTRODES

		Electrode									
		1	2	3	4	5	6	7	8	9	10
8	I (A)	0	0	0	0	0	0	0	130	0	0
	V(Volt)	27.9	41.0	37.7	70.2	118.0	237.5	92.6	2830.4	34.1	54.6
	R <sub>G</sub> (Ω)	---	---	---	---	---	---	---	21.77	---	---
9	I (A)	0	0	0	0	0	0	0	0	130	0
	V(Volt)	161.6	43.7	30.4	31.4	38.8	32.4	49.9	34.1	2492.6	37.6
	R <sub>G</sub> (Ω)	---	---	---	---	---	---	---	---	19.17	---
10	I (A)	0	0	0	0	0	0	0	0	0	130
	V(Volt)	32.2	126.3	105.8	125.2	91.4	62.3	44.8	54.6	37.6	2472.4
	R <sub>G</sub> (Ω)	---	---	---	---	---	---	---	---	---	19.02

interacting system. As mentioned before, electrodes 8, 9 and 10, are reserved to the GS network and are interconnected (see Fig. 6).

The three active electrodes of the GS network can be clearly seen in Fig. 9. In the vicinity of them, the potential gradient is very intense.

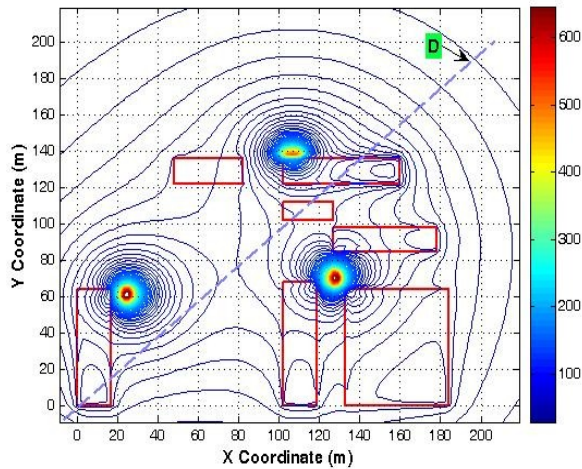


Fig. 9 GPR when one of the electrodes of the grounding system is excited. The figure also shows the diagonal D in magenta on the ground surface where the ground potential is evaluated.

With this new arrangement of the electrodes, we can newly calculate the potentials at the system. In this case, the main point is that voltages are, roughly divided by three, due to the division of the currents among the SS. Consequently, the potential of the three active electrodes is 891V (Table 2) and the electrode 6 acquires a potential, as a result of the interacting system of electrodes, that is found to be  $V_1 = 105V$  (Table 2).

Since ground potential at the point 2 is  $V_2 = 91V$ , this time the touch voltage at point 2 (Fig. 5) will be  $V_t = V_1 - V_2 = 15V$ , significantly lower than the one previously calculated.

To compare the effect on the GPR of associated conductors to adjacent buildings and also the interconnection of GS, Fig.10 shows the absolute potential curve along the diagonal line D, shown in magenta color in the Fig. 9. In all cases we assume that a current of 130A is released from electrode 8 to the ground.

The blue curve represents the ground potential along the diagonal D when electrode 8 is completely isolated. The red line records the ground potential when the other electrodes are taken into account, while the green curve shows the potential along the diagonal, where all GS electrodes are interconnected. The ground potential smoothing effect due to the interconnection between the GS electrodes can be seen very clearly. The most relevant data of the entire electrode system are shown in Table 2.

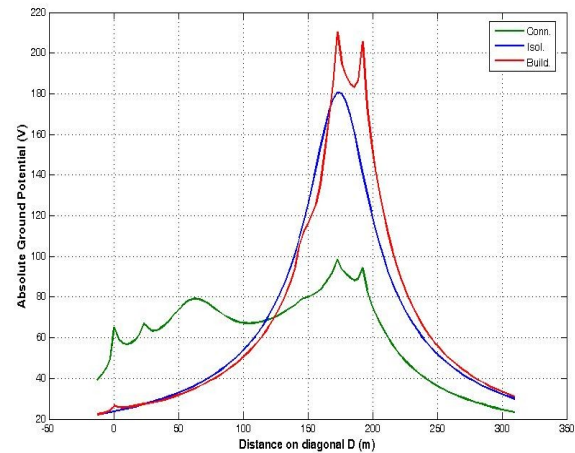


Fig 10. Ground potential profile along the magenta diagonal line D shown in Fig. 9

Finally, it should be mentioned that, in this paper, there has been used in all cases the same fault current (130 A), in order to make easier the comparison of the key points. However, the fault current depends sensitively on the grounding resistance  $R_G$ , which varies from one situation to another, especially in the case of interconnected electrodes, in which,



TABLE 2  
ELECTRICAL FEATURES OF THE ELECTRODE SYSTEM AT THE FAULT CONDITION

	<i>Electrode</i>									
<b>I (A)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>
<b>V(Volt)</b>	75.9	71.7	58.9	75.9	81.2	105.1	61.1	39.5	45.2	45.3
<b>R<sub>G</sub>(Ω)</b>	---	---	---	---	---	---	---	22.55	19.69	19.67

additionally to the effect of the buried conductors in the ground, it is necessary to make the parallel composition of the grounding resistances of the three electrodes.

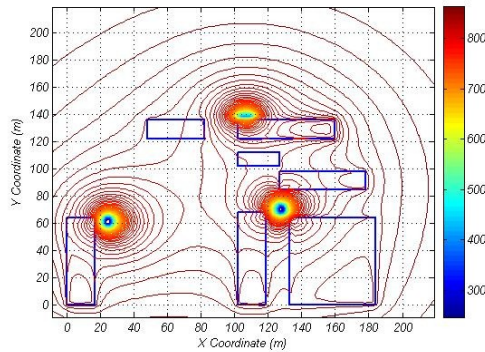


Fig. 11 Touch potentials profile on the ground surface.

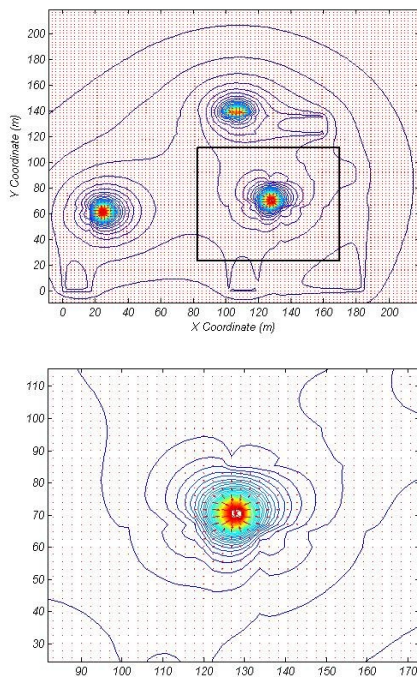


Fig. 12 Step potentials profile as the potential gradient vector field (upper panel). Detail of the grounds of electrode 9 (squared region on the bottom) in the lower panel.

The touch potential profile is obtained by subtracting the potential of the GS active electrodes 8, 9 or 10, to the ground potential shown in Fig. 9. The touch potential on the ground surface is shown in Fig. 11.

Finally, the step potential profile, obtained from the gradient of absolute potentials on the ground surface, is shown in Fig. 12. The upper panel shows the gradient vector field of the absolute potential. It can be seen that there only exist significant values in the vicinity of the active electrodes. In the lower panel, a detail of the gradient vector field is displayed in the vicinity of electrode 9.

#### IV. CONCLUSIONS

The equation (1), which corresponds to a system of conductors in mutual interaction in a semi-infinite medium in steady state, is solved using an integral formulation (EFIE) together with a MoM-based numerical method and a thin wire model for the electrodes.

The case of study corresponds to a real problem with GS interconnected electrodes and other nearby isolated electrodes which represent residential buildings, facilities and adjacent elements. From the model, the absolute potential on the ground surface has been found.

We performed a study of GPR values along the diagonal marked in Fig.9 and also the touch potential at point 2 (Fig.6) comparing three different situations in which the electrode 8 of the GS is activated: 1) electrode 8 isolated without interaction with any other, 2) electrode 8 isolated and interacting with the other electrodes of the system and 3) electrode 8 interconnected with the other electrodes of GS and interacting with the rest of the electrodes.

We have found that the presence of other electrodes, if passive, significantly altered the ground potential. Knowledge of the ground potential has allowed the calculation of step and touch potentials on the ground and found to have significant values only in the immediate vicinity of the GS electrodes, although the characteristics of adjacent buildings electrodes, even if they are isolated from the high voltage electrodes, must be considered to assess the potential transferred to those building. Additionally, the interconnection between ground electrodes, which causes the fault current splitting between all GS electrodes, significantly reduces the ground potential, smoothing the values of step and touch potentials allowing their values move away from the critical values given in the standard.

The innovation of this work is a method that helps determine ground potentials in complex systems, representative of networks in which there are two kinds of electrodes, some of them interconnected to the grounding

electrodes of the HV systems and others isolated. This is applicable to the urban areas of countries using TT systems, in which relevant isolated grounding electrodes exist, mixed together with HV electrodes.

In particular, the results provide more accurate voltage profiles around customer buildings, which is useful to determine the appropriate point to install the electrodes of secondary substations, in such a way that no dangerous touch and step voltage can occur at the customer premises.

Finally, it only remains to add that the method used in the calculations in this work have been applied to simulate the behavior of standard grounding electrodes in an experimental arrangement, within the framework of Tabón Project, sponsored by the companies Iberdrola Distribución, Iberdrola S.A. and ATISAE, and funded by the EEA grants and Norway Grants.

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